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Flipping the Classroom to Create a Student-Centered Learning Environment in Three Undergraduate Civil Engineering Courses

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A flipped classroom is no longer a novel idea, but engineering education has lagged in implementing this non-traditional course delivery method. Traditional engineering courses are typically offered in an instructor-centered environment which impacts everything from content delivery to student engagement and learning. A decade ago, we initiated a major project in curriculum reform that included flipping three second-year civil engineering courses: *Statics*, *Dynamics*, and *Deformable Solids*. These courses are foundational for all civil engineering students but, up to that point, had only been offered using traditional textbooks and lecture-based instruction. Flipping the classroom was driven by a desire to acknowledge what is known about active learning to push the courses to better fit today's engineering needs. The result of flipping the classroom had an effect far beyond simply switching the use of the student's time inside and outside of class. The traditional approach to course delivery falls short on engaging the students and in understanding where students struggle and what they know. To address the first two issues, the flipped classroom approach was selected and executed across all three courses. Implementation required adjustments at the university level to course scheduling, including finding classroom spaces suitable for group work. The schedule and workflows of each individual course were redesigned. The majority of class time was reserved for recitation periods where students work on problems in groups with the help of an instructional team. While we initially held one lecture per two-week module, eventually all reading, lecture, and passive activities were moved outside of class time. Establishing the class time as the place to do the work and emphasize problem solving strategies improved student's time on task and reinforced the main learning goals of each course.

This paper will layout the logistics of flipping these courses along with the changes made to the content. The redesign process offered an opportunity to rethink what content was important, what students could do, and the skills that the students should have at the end of each course. The material from the traditional lectures had to be condensed down to include only the main ideas of a topic that could fit in a video lecture ranging between 10 to 30 minutes, but the problem selection became much more critical to highlight the details of each topic. The alignment of the course environment with the learning goals was instrumental, and included the condensed lecture content, better problem selection, improved assessment strategies, enhanced student engagement, and more direct individualized instruction for all students. The flipped classroom has provided significantly more facetime with each student to understand and address their misconceptions and to fill in gaps in their background knowledge. We have also developed a mastery-based grading strategy that not only improves on traditional assessment strategies but also complements the learning environment by helping to direct student effort and motivation. The overall student experience has improved, and the new learning environment provides more flexibility for both the instructor and the student to achieve the learning goals of the classes.

Introduction

Over the past decade, an initiative aimed at introducing active learning opportunities in the foundational mechanics courses (*Statics*, *Dynamics*, and *Deformable Solids*), which are taken by civil engineering students in their sophomore year, has evolved into a complete redesign of the classroom environment, content delivery, and assessment approach in those courses. Available research on active learning and how people learned supported the effort. The redesign process presented many challenges in the first few semesters of implementation, but the student-centered learning environment that emerged is one that could be easily implemented in any institution.

The second-year mechanics courses were good candidates for a course redesign because they are based on a small number of concepts with many variations and a basic set of skills that support problem solving. The ideas tend to be conceptually difficult for students and the primary route to mastery is through problem solving. Prior to the redesign the courses were taught in a traditional instructor-centered environment that included three hours of in-person lectures each week with homework done outside of class time. Each course had one or two midterm exams and a final exam. The exams made up the majority of the grade. All class time was used for lecture wherein the instructor presented the theory and worked through examples. Students often zoned out during the theory part of the lecture and acted primarily as scribes of the examples. The important skill development happened entirely outside of the classroom, mostly without interaction with the instructor.

The lack of effectiveness from a primarily lecture style course has been well documented [1-4]. Further, the COVID-19 pandemic showed that lectures delivered remotely in a synchronous environment can be as effective as holding live lectures in a classroom [5]. The virtual environment also proved to many instructors that recording lectures was simple, opening up the possibility that students could access the information at a time that was convenient for them.

Engineering has started to move away from lecture only courses to offer courses that include active learning strategies. Active learning requires the students to become directly involved in the learning process instead of sitting as passive learners. The benefits and use of active learning in the classroom have been recognized in many different disciplines [3, 6]. Its use in engineering ranges from using clicker questions to think-pair-share activities to a completely flipped environment [7].

The flipped environment was attractive for the redesign of the mechanics courses because it allowed class time to be used for the most crucial learning activities (problem solving and student interaction) and made the supporting activities associated with content delivery more flexible. In the flipped environment, students can work on problems during class at their own pace while receiving support and feedback from the instructor when they need it [8]. Students can also work in groups during class, activating peer learning as one of the features in the environment. When students become actively involved in the learning process content retention improves and increased student performance is possible [9]. Flipped classrooms promote more student engagement in the learning process, promote deeper understanding of the material, and transform the classroom into a student-centered learning environment [3, 7].

As part of the course redesign, we also changed the assessment strategy to better fit the course objectives and change student motivation. A traditional testing environment exacerbates test anxiety, due to students focus on course grades, and promotes strategies (e.g., cramming for tests) that do not result in long-term retention or deep understanding of the material [10, 11]. The goal in redesigning the assessment style was to interrupt poor habits, blunt the focus on scoring, and make assessment more formative to provide better feedback for the students while helping the instructors better understand what each student knows and can do. Offering more regular and lower stakes testing has been shown to be beneficial to students [10]. We developed a mastery-based strategy based upon redundant demonstration of ability to achieve individual learning objectives that complements the activities done in the new classroom environment. The approach employs frequent assessment and feedback aimed at shifting the focus away from earning a high score and toward mastery of the course material.

Course Organization

Prior to the redesign, the courses were offered in a traditional lecture format with a traditional assessment strategy. Each course was worth 3-credits and met for either three 50-minute periods or two 75-minute periods each week. Class time was entirely devoted to lecture and assessment consisted of one or two midterms and a final exam. The course grade was based primarily on the exams. This common strategy seems efficient when viewed through a metric that emphasizes information delivery (often referred to as "butts in seats"). When the metric is student learning outcomes, this traditional approach is not ideal. The lecture environment often creates a barrier between the instructor and the student because it limits opportunity for them to engage one-on-one. It creates passivity in the classroom and leaves students without support when they finally engage the material (e.g., when they address assigned homework). Office hours outside of class suffer from logistical difficulties associated with aligning time of availability with times of student need. Further, the students most in need of help are often least likely to seek it out. The traditional environment often has a competitive aspect in which the only measure of success is an exam grade.

The course redesign process involved a period of planning and discussion among the faculty assigned to teach the courses and some faculty who taught the downstream courses that depend most directly on the outcomes from the mechanics courses. Implementation of the new course elements was gradual. *Dynamics* was the first course to undergo the complete redesign. This choice had some fortuitous consequences that might not have manifested had we started with *Statics*. In the first semester of implementation, some adjustments were made to *Statics* and *Deformable Solids*, but *Statics* was fully redesigned a year after *Dynamics* and *Deformable Solids* a year after that. The three courses have now been offered in the revised format for about ten years.

Initially, the redesigned courses were not completely flipped. It quickly became clear that it would be challenging to get students to complete the pre-class readings or assignments prior to starting a topic. Instead, we adopted a simpler goal to minimize lecture time in class and maximize problem solving time in class. To accomplish that goal, we divided class contact time into recitation periods, lecture periods, and assessment periods. During a recitation period lecture was forbidden, lectures were limited to one class period every two weeks, and assessment was done once every two weeks as well. Biweekly assessments suggested organizing the course in two-week modules, each one emphasizing a certain topic.

The lectures and assessments could be held in a large lecture hall while recitations were limited in size to accommodate the flipped portion of the class. For larger numbers of students, the number of recitation sections increased while lecture and assessment accommodated all students at the same time. For assessment this practice made common exams possible, minimizing the effort required for writing those exams. The course schedule was modified to include two 75-minute recitation periods and one 50-minute lecture/assessment period each week for a total of 3 class meetings in a week. The number of course credits did not change, but the additional 50-minute period was assigned as a mandatory section that had to be added for the students taking each course. The justification for additional seat time is similar to how physical laboratories are viewed within the Carnegie unit system—the out-of-class time associated with recitation time is less than pure lecture because a lot of the work is done in class.

One implication of this approach was that we needed different rooms for lecture and recitation. A quirk of the university's classroom reservation system resulted in needing to find a way to reserve the large lecture hall on a regular basis (not just once per week). The outcome was to have the lecture period for each of the three different courses assigned in the same time slot on the weekly calendar, but each class was assigned a different individual day. This schedule caused the start and end days for each 2-week module to be on a different day of the week for the three courses, an interesting but manageable feature. We would, for example, have the *Deformable Solids* lecture on Monday at 10:30-11:45, the *Dynamics* lecture on Wednesday at the same time, and *Statics* on Friday during that time slot. To the university that looks like full use of the lecture hall during the MWF 10:30-11:45 time slot, and the 75-minute recitations are typically held on different days, e.g., TuTh if the lecture is on Monday or Wednesday.

A second implication was that every two weeks we introduce a new module during a recitation period and wrap up the module with an assessment. Scheduling, then, puts the lecture associated with the module *after* the first recitation. That logistical quirk combined with the challenge of having only one lecture per module caused us to reimagine the role of the lecture in the learning process. In the old adage “tell them what you are going to tell them, tell them, tell them what you told them”, the lecture was closer to the “tell them” or even “tell them what you told them” than it was “tell them what you are going to tell them.” For students trained in the traditional linear approach, this feature offered a few challenges. During the Zoom part of the COVID-19 pandemic, we recorded all lectures, thereby finishing the transition to a completely flipped classroom. Upon complete flipping, the lecture period was converted to an additional work period for students to complete MATLAB computing projects or continue to work on the class problems. While there may be many ways to handle this course design problem, it serves as a reminder that classroom scheduling plays a huge role in how we conceptualize course delivery and classroom use.

The two 75-minute recitation periods each week are dedicated to students actively working on problems in a group setting. We manage the recitations with an instructional team that consists of one instructor and undergraduate teaching assistants (UGTAs). The number of UGTAs is proportional to the number of students in the recitation with a ratio of about 12-15 students for each UGTA. Recitation size can range from about 15 students to about 50 with a single instructor without running into a problem with instructor bandwidth. We have found that the ideal recitation size is somewhere between 30 and 50 students (depending on the quality of the space). The students are less self-conscious in an environment where many people are talking, and engagement tends to happen more readily.

Undergraduate teaching assistants are selected students who have recently completed the course. Because they have experienced the course as students, they know how the recitation sessions operate. We provide orientation at the beginning of the semester and provide them with detailed solutions to the problems that they can use to prepare for class. Additional training is done on the job as the need arises. The course instructors are always available in the classroom with the UGTAs. Most UGTAs serve for multiple semesters. Near peer TAs have proven to be very effective with instructor guidance.

This course structure has also been used at a second university for *Statics* for the last four years. At that university the class meets for three 50-minute periods each week. The recitation periods are shorter, but it is still a valuable use of class time for the students.

Classroom design is central to success in a flipped classroom. The recitation sections had to be placed in rooms with furniture capable of accommodating group work since the periods were active and students need to talk and work together. Further, the instructional team must be able to get to the students easily for one-on-one or one-on-few conversations. The lecture and assessment period could remain in a large lecture hall because students are not collaborating on those days and the instructional team does not need to move around.

The two-week module schedule includes six in-person class meetings, three each week. The order is typically: (1) recitation, (2) recitation, (3) lecture (now the additional work period), (4) recitation, (5) rehearsal exam, and (6) assessment. The rehearsal exam period is essentially a recitation but held in the format of the module assessment. The intention is to give a practice exam of similar difficulty to the assessment problem and encourage students to limit their resources to those available during the module assessment (we provide a standard crib sheet). During the recitation and rehearsal exam periods, the students are actively working in groups to solve new problems each period. They generally have examples in the course materials to get them started and the instructional team to help them when they get stuck or have questions. To maximize their effectiveness, the undergraduate teaching assistants are provided detailed, worked out solutions of the problems and undergo training on best practices for interacting with students. The undergraduate teaching assistants can handle the majority of student questions, but the instructor is always present to assist them.

Many students do not complete the problem of the day during recitation because the problems are designed to be challenging enough to keep the best-prepared students fully engaged. There are different strategies for recitation follow up. In *Statics*, for example, at the end of each recitation, the work that the students did not finish becomes homework and that makes up all problem-solving homework of the course. In *Dynamics* and *Deformable Solids*, we started with the same strategy, but noticed that a number of students were not completing the homework. We since changed the approach to one where we provide the complete solution (and video) to the recitation problem immediately following the recitation. Then one additional problem is assigned as homework for each module. Posting the solutions allows the students who did not get to the final answer to see how last parts of the problems are done.

The "lecture" period happens in the middle of each two-week module and is attended by the students and the instructors (but not UGTAs). This time can be used for students to work on anything they need to make progress on for the class, including the computing projects or recitation problems. The assessment session happens at the end of the two-weeks. The assessment is the only class period where the students work independently to solve a single problem from each module. This is the only class period that is quiet, and the students are allowed to use a sheet of handwritten notes or a formula sheet provided by the instructors to help them solve the problem.

Outside of class time, the students are expected to watch the lecture videos, read the notes, look through example problems, and finish or follow up on the recitation problems that they do not complete during class. At the start of each module new resources are posted to the Canvas page for the course. These resources include notes, examples, and lectures for the module covered in those two weeks. The students are encouraged to look through the resources prior to the first recitation of the module, but there is no formal check or test to ensure this happens. The recitation problems have been chosen so that students who did not look through the resources prior to class can still make progress during class time. In most instances, it is not until the first recitation that students start looking through the resources and use them to help with the problems. Many students operate on a need-to-know, just-in-time basis, so this set up works for them. Once they have started working on the problems and want to understand more about the theory or process, they go back and look through the resources with an initial understanding and better connection to the application of the current new topic.

Course Content

The theoretical content in *Statics*, *Dynamics*, and *Deformable Solids* is standard and was not to be impacted by the changes to the course; only the delivery method and the approach were to be changed. However, as we worked directly with students it was evident that plug-and-chug or recipe-based strategies were the norm for solving the problems in each course. Students were conditioned to find a formula and plug numbers into it. They would do well on an exam if they could make use of that strategy. A major aim of the course redesign was to help students develop into better and more rigorous problem solvers.

One of the advantages of including three courses in the redesign was that it enabled us to see how a lack of continuity between courses and sometimes even between subjects within each individual course was preventing students from fully understanding basic principles. Finding and reinforcing the common strands was part of the redesign effort, particularly in the area of assessment.

The reduction in lecture time dictated that the new resources could cover only the foundational principles—the theoretical big picture. The course notes were reserved for the main ideas on each module topic. The example, recitation, and assessment problems were carefully selected to bring in details and dive deeper into each topic. This shift in perspective from having to cover every detail on a topic to letting the students explore and discover the details through problem-solving was significant for many reasons.

First, it was significant for creating a deeper understanding of each topic because students were now having conversations with the instructors about where details or special situations arose relative to a problem application. They could see how it impacted the problem solution and think about how it differed from past problems. These just-in-time mini-lectures happen at a time of curiosity of the student (or group of students) and are prompted by them. They encounter these ideas in recitation where the instructional team is present to support them. Students can get answers to their questions when they are trying to understand and apply the material. This mechanism also provides the instructional team with a better understanding of where each student is struggling rather than trying to address typical misconceptions to an audience of all students.

An example of letting the problems show the nuances with a problem type happens early in *Statics* when solving problems with static friction. The notes explain that friction force will be at its maximum value (equal the normal force times the static coefficient of friction) if there is impending motion. Otherwise, the friction force is exactly what is needed to maintain equilibrium. The students pay no attention to that idea and commonly assume it is always the maximum value (perhaps based on something they learned in their physics course). When they approach a problem where the static friction force is less than the maximum value, there is an opening for a great conversation about friction and why the maximum value is not always appropriate. The students hear this conversation because they are ready for it. An example of understanding a student's struggles better often comes from the conversations with students trying to set up vector components for a force vector. The students often struggle with the trigonometry calculations, not with understanding vectors or how to use them in force or moment equilibrium. We often imagine that it is the latest topic that causes a student to struggle when, indeed, it is often background information.

Second, the shift in perspective to focus on the fundamental principles informed the problem-solving approach and led to the mastery-based grading approach that we implemented. The goal was to help students better understand the basic principles, to see the big picture, and to make the connections from problem to problem and course to course. Rather than categorizing problems by physical phenomena, the course content was organized into *mastery objectives* that captured the common strands of the theory that were applicable to all problem categories. Specialized topics were addressed as they came up in specific problems. For example, we do not lecture on things like units or vector algebra. Instead, we employ just-in-time teaching of those concepts in the context of problems in which they appear. To create rigor and continuity amongst the modules a problem-solving strategy organized around the mastery objectives was created for each course. The mastery objectives in each course are evident when breaking down problems into explicit pieces needed to solve an entire problem. Each of the three courses has a set of mastery objectives unique to the needs of that course. The mastery objectives evolved over the first few semesters to what they are now and comprise a solid, detailed problem-solving strategy that can be applied to all problems in that course. The brief name of the mastery objectives for the three courses are listed in Table 1.

The mastery objectives are used to solve every problem in each course. The students organize their solutions following these objectives for all recitation and assessment problems. Assessments are completed by the students and graded by the instructor objective by objective. The posted examples are organized following the objectives as well, so the students learn the objectives well and see how they apply to many different problems. They understand that the problems can all be solved using the same pieces but have different details based on the physical attributes of each one. This approach creates consistency amongst problems within a course. There are also several of the objectives that are repeated and required in each of the three courses to create continuity amongst the three courses and all mechanics problems.

Table 1. *Course Mastery Objectives*. This table gives the name for each of the mastery objectives.

Statics	Dynamics	Deformable Solids
A. Modeling	A.1. Geometry and prob. setup	A.1. Geometry and prob. setup
B. Solution strategy	A.2. Initial conditions	A.2. Boundary conditions
C. Problem geometry	A.3. Modeling and constraints	A.3. Kinematics
D. Free body diagrams	B. Describe position vector	C. Free body diagram
E. Force equilibrium	C. Compute velocity and accel.	E.1. Force equilibrium
F. Moment equilibrium	D. Free body diagrams	E.2. Moment equilibrium
G. Distributed effects	E.1. Balance linear momentum	F. Strain-displ. relationships
H. Solution process	E.2. Balance angular momentum	G.1. Constitutive equations
I. Internal forces	F.1. Vector algebra and calculus	G.2. Properties of areas
J. Units & conversions	F.2. Integrate over spatial domain	H.1. Derive differential eqn.
K. Systems	G. Conservation of momentum	H.2. Implement BCs
L. Notation	H.1. Classical soln. to diff. eq.	I. Execute algebra and calculus
	H.2. Natural freq. and modes	J.1. Stress formulas
	J. Compute dynamic response	J.2. Multiaxial stress-strain
	K. Compute energy and work	K. Compute relevant response
	L. Apply work/energy principles	

Grading for Mastery

Identifying the mastery objectives, requiring them for all solutions, and assessing every other week results in a lot of data and information on how each student approaches problem solving. Instead of recording performance on each assessment as a single score, we look for and track demonstrations of mastery objective by objective. This approach helps students to break away from the scoring mentality and focus better on their strengths and weakness as reflected in their progress with respect to the mastery objectives. Mastery is defined as a redundant demonstration of an ability to perform a given objective. The course grade is based upon the total number of objectives mastered.

In practice, mastery looks like correctly executing a certain mastery objective multiple times on different module assessments (and, therefore, different problems) during the semester. Each module assessment has a single problem and activates some (but possibly not all) of the mastery objectives. The work on each objective is evaluated with a simple rubric that favors a complete and correct demonstration but allows some credit for small errors. Each objective is weighted for a given problem based upon the difficulty associated with the objective in the context of that problem. The number of correct demonstrations required for mastery is established by the instructors as being enough to be confident that a student will be successful on that objective in a future problem. In *Statics* we require roughly five complete and correct demonstrations of an objective to claim mastery. In *Dynamics* and *Deformable*

Solids there are more mastery objectives, and we consider three complete and correct demonstrations to claim mastery. Again, these levels can be set by the instructors based upon the nature and logistics of the course.

Mastery-based learning is often associated with mastering a concept before going on to the next more advanced one (e.g., a student must succeed on ten successive problems of a certain type in order to move on). That model would be difficult to implement in courses like these. In our model, mastery develops in parallel for all of the mastery objectives. As students are assessed every two weeks and each problem reflects the mastery objectives, the instructors can track how each student progresses towards mastery. In an ideal world, each student would have to show that they could do each objective correctly for each problem in one course before moving onto the next course, but that does not fit into the current higher education model. The course grade reflects how far the student gets with mastery, with a minimum requirement needed to pass the course.

To make an assessment method based on redundant demonstrations work, assessment must be done frequently. Assessing every other week creates roughly seven assessment opportunities during each semester, and each course has a final exam that creates additional assessment opportunities. This results in the students being tested on roughly ten problems for each course in one semester. They are now tested on more problems than in the previous traditional offering and receive feedback on those attempts, plus assessments are designed to provide more problem opportunities than needed to reach mastery (roughly twice as many). This design was done intentionally so that mastery was attainable within the semester time constraint. The students have enough opportunities to succeed so that if they have a bad day or are still learning the topic, they can still get to mastery. The mastery system is strictly positive. A bad performance is viewed as nothing more than a lost opportunity to demonstrate mastery. It does not take away from previous demonstrations or in any way lower the grade. The frequency of assessment and the non-negative approach to evaluation reduces the level of test anxiety.

This grading approach has been a mindset shift for students because they do not receive a percentage or letter grade for their work, but rather a breakdown of how they did for each objective. After each assessment, the students receive a dashboard that visually shows how they are doing in the course, which objectives they are doing well on, and the areas that they need to work on. The feedback is much more informative, but it does require students to depart from their belief that receiving a letter grade tells them exactly how they did on a problem. The details of the mastery-based grading system, including the method of feedback, are included in a previous paper [12].

Coordination across all three courses

We have used this new course design for over the last decade. It has been manageable, in part, because we employ a team-teaching model. Team teaching is not common in higher education, but it is a very beneficial and effective model. The redesign of the courses created multiple sections of each course instead of the one large section traditionally offered. Instead of assigning the multiple sections to one instructor, the three courses were now considered a joint effort. Initially, there was a team of three to four instructors assigned to the three courses, with each course involving at least two instructors and with some of the instructors being involved in more than one course. The team members had the opportunity to work together to develop the materials and to ensure consistency across the courses. This model requires a slightly different view of faculty teaching load. The faculty in this setting have more facetime with the students, but the prep effort is distributed among the team members. The recitation environment also lessens the need for office hours and reduces the number of email questions from students because class time is spent addressing most issues students had. It also solves the issue of a faculty member needing time off (e.g., for illness, jury duty, childcare). In a team-teaching environment, the other team members can seamlessly cover for an absent instructor. The students become very familiar with the team of faculty because they have them for multiple courses and are generally comfortable interacting with any of them. Overall, this model is favorable with respect to faculty workload.

Coordination of content and learning environment across the three classes is also beneficial. In the first year, only *Dynamics* had been converted to the new student-centered learning environment. Student reaction to the change was quite negative. Having been trained in the traditional environment, anything different from that was unsettling. However, once the environment, materials, and notation were adjusted for *Statics* and *Deformable Solids* in the following two years, the growing pains quickly dissipated. To this day, students still need some adjustment in *Statics*, but the two post-requisite courses experience almost no adjustment period (possibly with the exception of transfer students who are experiencing the environment for the first time). While students are initially skeptical of mastery-based grading, course feedback shows that they ultimately really like it and appreciate it in a way that is consistent with the design objectives. Students come to class excited to work on new problems. The learning environment functions as a quasi-social one, but most of the conversations are about the problem of the day. Attendance and time on task during recitation tends to be excellent.

The shift to using mastery-based grading, organized around the mastery objectives, promoted a new problem-solving approach for each course and a shift in mindset for how mechanics problems should be solved. The problem-solving style was not adequately supported by any textbooks on the market. We developed our own course notes and worked out examples so that our learning strategies would not have to compete with the book. Creation of the course materials was a significant task for the faculty, especially in the first year each course was redesigned. This additional workload is also why it took three years to transform the three courses to the new model instead of changing all three in the first year. The instructional team members assigned to each course were responsible for creating notes and examples (the "textbook") along with solutions for all assigned problems and assessment problems. Eventually, the team recorded lecture videos as well when that part of the course was moved online. Textbooks for *Dynamics* and *Deformable Solids* based on the course notes developed for this project will be publicly available soon.

The students benefitted from this coordination and continuity because they understood how to use the resources, they were familiar with the notation, and they understood the concept of mastery-based grading (and the associated mastery objectives). Features of the learning environment that were previously perceived as unusual are now viewed as normal to the students. Course evaluations suggest the sophomore-level mechanics courses are among the most liked by students in the program. Consistency of notation and style among classes eliminated the need for review of previous material in the first few weeks of class. *Dynamics* and *Deformable Solids* introduce new concepts on day one of class. The students know how to prepare and come in ready to work during recitation, and they are familiar with the grading style and expectations of their work. Each course scaffolds on what is done in the other courses in a way familiar to the students to further their learning while also supporting and building on the background knowledge they have. In a traditional environment, where each course is designed independently it can be challenging for students to make the connections to past concepts they have learned. Also, the difference in expectations between instructors can be confusing to students, especially in their 2nd year when they are only beginning their journey in engineering coursework. Creating a consistent method for assessment and evaluation of work across multiple courses sets the tone and expectations for the students and they rise to that level.

Outcomes of the student-centered environment

It is challenging to compare student grades or learning outcomes from before and after the change of environment because almost everything about the course has been changed. The type of coursework is different, the classroom environment is different, the assessment style is different, and the inputs into the final grade are significantly different. While the problems done in the course are fairly standard undergraduate mechanics problems, they are often stated differently, and the solution paths are often quite different from what one finds in traditional textbooks. However, there are outcomes from the current model that are worth noting.

Engagement. The first outcome is the shift in course engagement. Creating and documenting engagement was a big emphasis of the redesign. Engagement can take many forms, but some include providing opportunities for students to engage with the material, with each other, or with the instructors. The recitation environment allows a more personalized interaction to happen between the faculty and each student. It allows students to be more comfortable expressing what they don't understand and to ask for help. From an instructor perspective, this has been invaluable to better understand what each student is struggling with. Students also find a lot of value in the recitation environments. They do not want to miss the opportunity to work on the problems in the supported environment. Attendance is tracked for every class period because it is a way to promote engagement with the material. The most recent offerings of the courses show a very high percentage of attendance as provided in Table 2.

Table 2. *Recitation Attendance*. This table shows the percentage of students that attended each recitation period in Fall 22. Rehearsal is a recitation where the problem of the day is in the format of a practice exam.

	Statics (N=114 students)	**Dynamics (N=34 students)**	**Deformable Solids (N=33 students)**
Average Recitation attendance	92% (N=22 recitations)	91% (N=21 recitations)	93% (N=21 recitations)
Lowest Recitation attendance	77%	82%	85%
Average Rehearsal Attendance	95% (N=7 rehearsals)	100% (N=7 rehearsals)	99% (N=7 rehearsals)
Lowest Rehearsal Attendance	89%	100%	97%

As the table shows, most students attend all class periods. The assessment periods are not included, but those generally have full attendance (or those who miss schedule a makeup). In *Statics*, the lowest recitation attendance was during a work period that happened late in the semester. During a work period there are no new problems or projects assigned, so it is likely that students did not feel they needed the extra help with the work for that module. The lowest rehearsal attendance was for the last rehearsal exam, which students may have missed because they did not feel as though they needed to practice for the last assessment. The two lowest numbers also occurred on Fridays (due to previous holidays) which Fridays typically have a slight drop in attendance. For *Dynamics* and *Deformable Solids,* the lowest recitation attendance occurred in the latter half of the semester. Sometimes students miss the recitation the day after a module assessment (i.e., the first recitation of the new module), but such misses are rare. Attendance at rehearsal exams in *Dynamics* and *Deformable Solids* was nearly perfect for the FA22 semester.

Feedback. The second outcome of the new environment is better, more detailed feedback for the students and more insightful grade data for the faculty. As a result of the mastery grading system each student receives individualized feedback after each assessment on how they did on every objective for that problem. The feedback tells them whether they (a) did it completely and correctly, (b) had a minor calculation error, (c) had a minor conceptual error, (d) had a major conceptual error, or (e) did not provide evidence for that objective. The students can use the feedback along with the posted solution to understand what they did well and the areas that they need to work on. We also ask students to do a self-assessment after every module assessment in which they grade themselves with full access to the solution, write comments about what went wrong and how they plan to adjust their learning strategies. We also ask about how they engage the course materials in their studies (e.g., Did you watch the lecture videos? Did you read the relevant sections of the textbook at least once? Did you review problems starting from a blank sheet?) [13].

The instructors also have the same data for every student and can use the data to see trends in the class and provide individualized help to students. The individualized help happens during conversations with each student about their feedback. However, looking at the data for the class can provide insight into how the class is doing in each area, how difficult the assessment problem was, and if there are items that should be revisited or re-emphasized.

Figure 1 shows recent student performance data on *Statics* assessments. Each subplot is associated with one mastery objective (indicated in the upper left corner). The charts show the percentage of students earning each score using the ‘a’, ‘b’, ‘c’, ‘d’, or ‘e’ ratings described previously. The rating scores earned by students on each assessment are indicated with the following symbols: ‘a’ large solid circle, ‘b’, large open square, ‘c’, small solid diamond, ‘d’ small open circle, ‘e’ small solid circle).

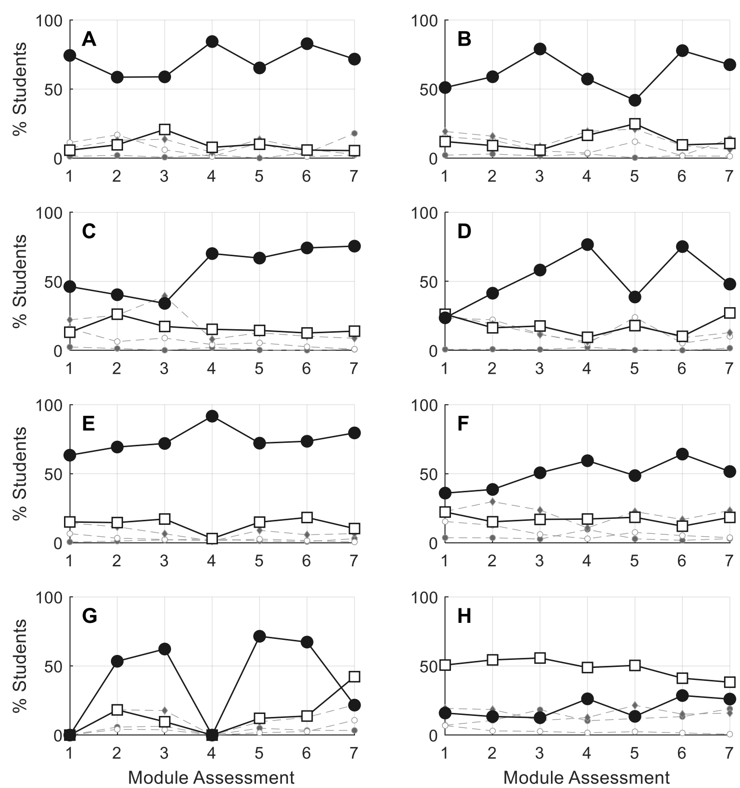

Fig. 1. *Module Assessment Results in Statics*. The results are the average over six semesters with N = 601 students. The ordinate is the percentage of students getting each score (‘a’ large solid circle, ‘b’, large open square, ‘c’, small solid diamond, ‘d’ small open circle, ‘e’ small solid circle). Each subplot is associated with one mastery objective (A – H), indicated in the upper left corner. The abscissa for each plot is the module assessment number (1 – 7). The scoring rubric: (a) complete and correct, (b) minor calculation errors, (c) minor logic errors, (d) major conceptual errors, (e) no work shown.

The ‘a’ and ‘b’ ratings are shown with larger symbols because they indicate success with the objective. The remaining ratings (‘c’, ‘d’, and ‘e’) are shown smaller and subdued but are included to complete the information. Each point on each graph is the average over six semesters with the number of students indicated in Table 3.

Table 3. *Statics class sizes*. This table shows the number of students included in the data from Fig. 1.

	FA19	SP20	FA20	FA21	SP22	FA22
Number of Students	48	126	92	130	93	112

There is variation in performance from one semester to the next, in part because the problems on the module assessments are different and in part because there is variation class composition. However, we have found that students performed similarly across the six semesters. Hence, the average over all semesters reliably represents student performance. The assessment results show some notable trends and provide insight into student progress over the semester.

The students show general improvement in all objectives over the course of the semester, showing learning gains for students over the semester, which is the intent of the mastery system, while dividing the data in a way that is informative to the instructor. For example, comparing objective E—Force Equilibrium and objective F—Moment Equilibrium suggests that students comprehend force equilibrium better than moment equilibrium. The instructors can use these results to determine how the students are doing and if they are improving. The performance breakdowns by objective also provides the instructor with important feedback on the areas to reinforce with the students in subsequent instruction.

Scores for objectives A, B, D, F, and G drop between MA 6 and MA 7. This trend provides impetus for the instructor to question if the result is a common trend for the course (for example, caused because students have already demonstrated mastery and are less concerned about performance on the last MA) or if this artifact was specific to the assessment problem (specifically, the problem may have been more difficult, for some reason, than those tested earlier).

The same type of information is available for the other two courses, but it is slightly more difficult to interpret. In *Statics* almost all of the objectives are available on every module assessment (note that objective G was not available in MA 1 or MA 4 in any semester in Fig. 1), meaning that each objective is assessed around 10 times (including the final exam). In *Dynamics* and *Deformable Solids* not all objectives are available for all problems and hence the amount of redundancy is less. While there is still plenty of redundancy to determine mastery, the outcomes are not continuously sampled in these courses. In general, we try to provide twice the number of opportunities for each mastery objective relative to what is required to complete the demonstration of mastery.

Adaptation to remote learning. One final outcome of the new environment was the ability of the three courses to easily transition to an online format when required. There were minimal changes that had to be made to fully convert each one to a synchronous online course. The lectures that were happening during class time were recorded and posted, but otherwise the course schedule and class time was spent the same. Breakout rooms were utilized for recitation and the instructional team could join and answer questions. The assessments could be done virtually during the class time using Zoom. That mastery system and feedback style was kept the same to encourage students to make progress on the course concepts throughout the entire semester.

Student Feedback

Near the end of each semester we ask student to respond to a survey that asks for feedback on all of the pedagogical features of the classes. The student comments on this survey correlate very well with the standard university course evaluations (but this is a different instrument). These comments give a good picture of how the students experience the learning environment and they let us know if the pedagogical elements we have designed are working for the students. The surveys over many years show consistently that the students understand how the learning environment benefits them and they show, overwhelmingly, that the students like this environment. The following comments are about the flipped classroom environment:

> "I really like having the opportunity to work on problems and ask questions during a dedicated time. It felt very supportive compared to my other classes where sometimes I would leave and not be sure how to work on a problem. I also really liked my table group; I felt like I learned a lot with them." (*Dynamics* student, FA22).
>
> "I liked the entire set up of the class. I liked being able to work with my group to solve problems and get some guidance from the TA's and instructors when we were struggling." (*Dynamics* student, FA22).
>
> "Recitation really provided me with a regular opportunity to really try problems often and get help when I needed it. It wasn't mind numbing like some recitations I've had where the teacher gives us the answer at the end but wasn't silent and rigid like a quiz either. It felt fun and collaborative to be there. The UGTA's made me more comfortable asking questions and the professors seemed to really care about where I was and how I felt in the class. (*Dynamics* student, FA22).
>
> "This was a great way to get hands on learning and learn how to problem solve on the fly. Also, there are usually questions that develop from the lecture/reading material and the open environment allows a lot of discussion that helps to understand concepts." (*Deformable Solids* student, FA22).
>
> "It was helpful to be able to work in a group to solve though problems. It was also nice to have instructors and TAs that could help answer questions." (*Deformable Solids* student, FA22).

Individual student feedback is much more useful that statistical feedback because it gives specific rationale for why certain course elements work or don't work for them. This feedback has led to numerous improvements in the way the course elements are implemented.

Conclusion

The student-centered learning environment has provided an opportunity to rethink class format and content delivery in three second-year mechanics courses. The courses have been flipped and mastery-based learning used to promote progress and growth in the course concepts rather than just correctness. This instruction better fits the needs of today's students by providing a more flexible use of class time with opportunities to interact and receive immediate help when needed. The result is an improved experience for both the student and the instructors to work towards achieving the learning goals of each course.

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